MOSQUITO PREVENTION ON IRRIGATED FARMS

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Several members of the task force made major contributions to the bulletin. The introduction was prepared by M. B. Rainey and A. D. Hess. Mr. Rainey also prepared the section entitled "Nature and Extent of Irrigation-Mosquito Problems," except the part dealing with the effects of mosquitoes on farmworkers and livestock, which was written by W. C. McDuffie. Howard Haise prepared the section covering relationships of mosquito prevention to irrigation agriculture, except the part on drainage, which was prepared by Tyler Quackenbush, Soil Conservation Service. The section on relationships of mosquito prevention to aquatic wildlife conservation was developed by A. D. Hess and Lee Yeager. The basic principles and practices for mosquito prevention outlined in the bulletin were adapted by Mr. Rainey from a recommendation of the American Society of Agricultural Engineers entitled "Principles and Practices for Prevention and Elimination of Mosquito Sources Associated with Irrigation," which was prepared in 1958 by the Committee on Irrigation System Design for Mosquito Control, Irrigation Group, Soil and Water Division.

Other members of the Subcommittee on Vector Control contributed their knowledge and experience to the preparation of the bulletin. Since their number precludes separate mention, the members of the task force express appreciation for the cooperation and assistance of numerous individuals, who provided constructive criticism and suggestions.

No claim is made for originality in much of the information presented in the bulletin. It has been developed from the research and experience of many individuals and agencies. The sources are far too numerous to list individually, and this means is taken to thank all those who have contributed directly or indirectly to the bulletin.

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Illustration on cover shows Boise, Idaho, irrigation project. Aerial view looking northwest toward Nampa-Meridian irrigation district. In foreground is New York Canal running toward Lake Lowell.

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MOSQUITO PREVENTION ON IRRIGATED FARMS

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In many areas, particularly in the West, the expansion in irrigation agriculture has been accompanied by an increase in the production of mosquitoes. These bloodsucking insects have a serious impact on the health, comfort, and economic welfare of people. They also hinder agricultural, industrial, and recreational activities and greatly reduce the overall benefits of irrigation developments. The irrigation-mosquito problem is being intensified by the continuing expansion of irrigation agriculture, the increase in human population, the acceleration of urbanization and industrialization, the development of insecticide resistance in mosquitoes, the growing concern over insecticide residues in food and water, the rapid expansion in outdoor recreational activities, and the public's increasing demands for a more comfortable and healthful environment.

Natural mosquito-producing habitats occur in most irrigated areas, but experience has shown that manmade rather than natural habitats are usually responsible for excessive mosquito populations. These manmade mosquito sources are most often caused by faulty irrigation, drainage, and management practices.

Mosquito sources are often associated with both the engineering and agricultural phases of irrigation, including storage reservoirs, conveyance systems, drainage systems, and farm irrigation. The ultimate solution to mosquito problems associated with irrigation must be based primarily on source-reduction measures aimed at eliminating or modifying aquatic habitats. In recent years it has become increasingly evident that this requires close and continuous coordination between those interested in mosquito control and those concerned with improving irrigation agriculture and related interests, such as fish and wildlife conservation and outdoor recreation. Although conflicts sometimes develop between mosquito control and water users, there are often ways to mutually accomplish the major objectives of all groups concerned. Public interest demands that mosquito control be coordinated with irrigation water uses to the end that maximum benefits may be provided for the greatest number of people. Although solutions may not be readily apparent for certain types of problems, they can be solved more rapidly through a coordinated attack based on a thorough knowledge of mutual interests.

Mosquito prevention on irrigated farms is only one part of the overall irrigation-mosquito problem. This bulletin provides information on (1) the overall importance of irrigation-mosquito problems, (2) manmade mosquito sources on irrigated farms, (3) relationships of mosquito prevention to good irrigation agriculture and aquatic wildlife conservation, and (4) basic principles and practices for mosquito prevention on irrigated farms. It is intended as a basic reference and guide for agricultural extension agents, managers of mosquito abatement districts, soil conservation technicians, and other technical and semi-technical personnel in public health, agriculture, fish and wildlife, and related fields concerned with the development and utilization of irrigation water on the farm.

NATURE AND EXTENT OF IRRIGATION-MOSQUITO PROBLEMS

Public-Health and Socioeconomic Importance

About a dozen species of mosquitoes associated with irrigation in the United States are of public-health importance because of their ability to transmit disease or because of their pestiferous biting habits. Encephalitis, commonly known as sleeping sickness or brain fever, is now the most important mosquitoborne disease in the United States. Mosquitoes obtain the encephalitis viruses from birds and other wild vertebrates and then transmit them to horses and humans. No effective chemotherapeutic measures for preventing or treating human cases are known; and some individuals, particularly children, who recover from the disease suffer permanent mental disability.

Three principal types of mosquitoborne encephalitis occur in the United States. Eastern encephalitis (EE) occurs principally in the Atlantic and Gulf Coast States from New Hampshire to Texas, but sometimes extends as far inland as Wisconsin. St. Louis encephalitis (SLE) occurs chiefly west of the Mississippi River and in several of the Central States and Florida. The third type, western encephalitis (WE), is confined primarily to the States west of the Mississippi River.

Mosquitoes such as *Culiseta melanura* and several species of *Aedes* may be involved in the transmission of EE. The principal vector of both SLE and WE in the Far West is *Culex tarsalis*, which is abundant in many western irrigated areas. In the Central States, *Culex pipiens* and *Culex quinquefasciatus* are important in the transmission of SLE in urban areas. Both of these species are produced in irrigated areas, particularly where stagnant and foul water, such as sewage effluent, is used for irrigation. *Aedes* and other irrigation mosquitoes may also be secondary vectors of encephalitis. WE and SLE are endemic in many western irrigated areas, and outbreaks of WE among horses and of both WE and SLE among humans have been rather widespread. In recent years encephalitis outbreaks have occurred in irrigated areas in the Texas High Plains (1956 and 1963), in the Intermountain States (1957), in the Lower Rio Grande Valley (1957), in Utah and New Mexico (1958), and in Wyoming (1960).

In past years serious outbreaks of malaria in the Southeastern States were associated with improperly prepared reservoir basins. Malaria has also been related to irrigation in several States, including California, New Mexico, and Texas, and in the rice-growing areas of the Mississippi Delta. This disease has been almost eradicated from the United States, and at present malaria transmission is not important in irrigated or nonirrigated areas.

The malaria vectors *Anopheles quadrimaculatus* in the East and *Anopheles freeborni* in the West are still prevalent in some areas where favorable habitats are present. These mosquitoes constitute a potential hazard for establishing new foci of malaria transmission, particularly where the disease may be reintroduced from foreign countries. This was well illustrated at Lake Vera in California during the summer of 1952, when 35 cases of malaria occurred among Camp Fire Girls. The source of their infections was traced to a soldier who had recently returned from foreign duty and had an attack of malaria while camping near the lake.

Several vicious biting mosquitoes, including *Aedes vexans, Aedes dorsalis,* and *Aedes nigromaculis,* occur in large numbers in many irrigated areas. These mosquitoes often create public-health problems in addition to transmitting specific diseases. For example, a study made by the U.S. Public Health Service in irrigated areas in northern Montana revealed that in three-fourths of the families surveyed, mosquitoes severely annoyed both adults and children and interfered with their normal outdoor activities during the summer. Mosquito bites caused some injurious reaction in 8 out of 10 people interviewed. In one section, 40 percent of the individuals examined by a physician had secondary infection from mosquito bites. Some individuals, particularly children, required medical attention and sometimes even hospitalization for treatment of secondary infections and occasional allergic reactions to mosquito bites.

In addition to their public-health importance, mosquitoes reduce the production efficiency of irrigated farms. Their biting limits the efficiency of farm laborers and other outdoor workers and may depress land values. Crops sometimes cannot be harvested properly or at the optimum time because of mosquito annoyance. Dense populations of blood-sucking mosquitoes interfere with feeding activity and drain the vitality of farm animals and poultry, resulting in reduced meat, milk, and egg production.

Even greater losses may result from the diseases mosquitoes transmit to livestock. Mosquitoes are vectors of encephalitis, anaplasmosis, fowl pox, and several other serious diseases that kill large numbers of farm animals and poultry every year. Thus, mosquito control is of interest to the farmer from the standpoint of both his health and his economic welfare.

Irrigation mosquitoes also cause economic losses in urban areas by reducing the efficiency of industrial workers, lessening the value of real estate, reducing attendance at outdoor business establishments, such as drive-in theaters and eating places, and restricting outdoor recreational activities.

The economic importance of irrigation mosquitoes is further illustrated by expenditures for their abatement. For example, in California over $6 million is spent annually to control mosquitoes. Most of this control activity is carried out in irrigated areas. It has been estimated that at least twice the amount of present expenditures would be required to provide adequate control throughout the State. Approximately $200,000 is spent each year for mosquito abatement in a few irrigated areas in Utah. Many urban communities in other western irrigated areas spend large sums of money each season for chemical control measures to provide partial protection from mosquitoes. Individual families also spend sizable amounts of money each summer for household sprays, mosquito repellents, livestock sprays, and medicine for treating mosquito bites.

Biology of Irrigation Mosquitoes

Irrigation mosquitoes represent four important genera or groups: *Anopheles*, *Culex*, *Aedes*, and *Psorophora*. All mosquito species have four distinct stages in their life cycle: Egg, larva ("wiggler"), pupa ("tumbler"), and adult (fig. 1). A characteristic common to all mosquitoes is that they live in water continuously from the time the eggs hatch until the adults emerge. They are generally found in shallow water with abundant vegetation and flotage and where they are protected from wave action. They do not occur in the deep open waters of lakes, ponds, or streams.

On the basis of egg-laying habits, mosquitoes may be divided into temporary-water and permanent-water species. The *Aedes* and *Psorophora* are temporary-water breeders, which deposit their eggs on the saturated soil of areas from which surface water has receded. In contrast, the *Anopheles* and *Culex* usually lay their eggs on the surface of permanent and semipermanent bodies of water. Hatching of the *Aedes* and *Psorophora* eggs is stimulated by subsequent floodings. The eggs of these mosquitoes may remain dormant for long periods, sometimes for several years if conditions are unfavorable for hatching. Normally the eggs hatch more or less simultaneously when they are flooded, and for some species a new brood may be produced by each flooding during the summer. *Anopheles* and *Culex* eggs usually hatch within a few days after oviposition. The time between hatching of eggs and emergence of adult mosquitoes varies with species and environmental conditions, especially water temperature. Development of the aquatic stages may be completed in 4 or 5 days in hot weather, whereas several weeks may be required in cool weather. *Aedes* and *Psorophora* mosquitoes generally develop more rapidly than *Anopheles* and *Culex*.

Adult mosquitoes mate soon after emergence. The females begin seeking blood meals, which most species require before laying eggs. The biting habits of adult mosquitoes vary with the species. *Anopheles* and *Culex* feed mainly at night, whereas *Aedes* and *Psorophora* feed both at night and in the daytime. Most species exhibit a peak of biting activity during a 1- or 2-hour period immediately after sundown. *Aedes* and *Psorophora* are aggressive and vicious biters of both man and livestock. *Culex tarsalis*, the common encephalitis mosquito, feeds readily on a wide range of hosts, including man, wild and domestic birds, and livestock.

The flight range of mosquitoes varies widely with the species and environmental conditions. The direction and distance of travel are greatly affected by availability of food and shelter and by wind conditions. Availability of food is probably the most important factor affecting the movement of mosquitoes on irrigated farms. If an adequate food supply is close to the production sites, adult mosquitoes

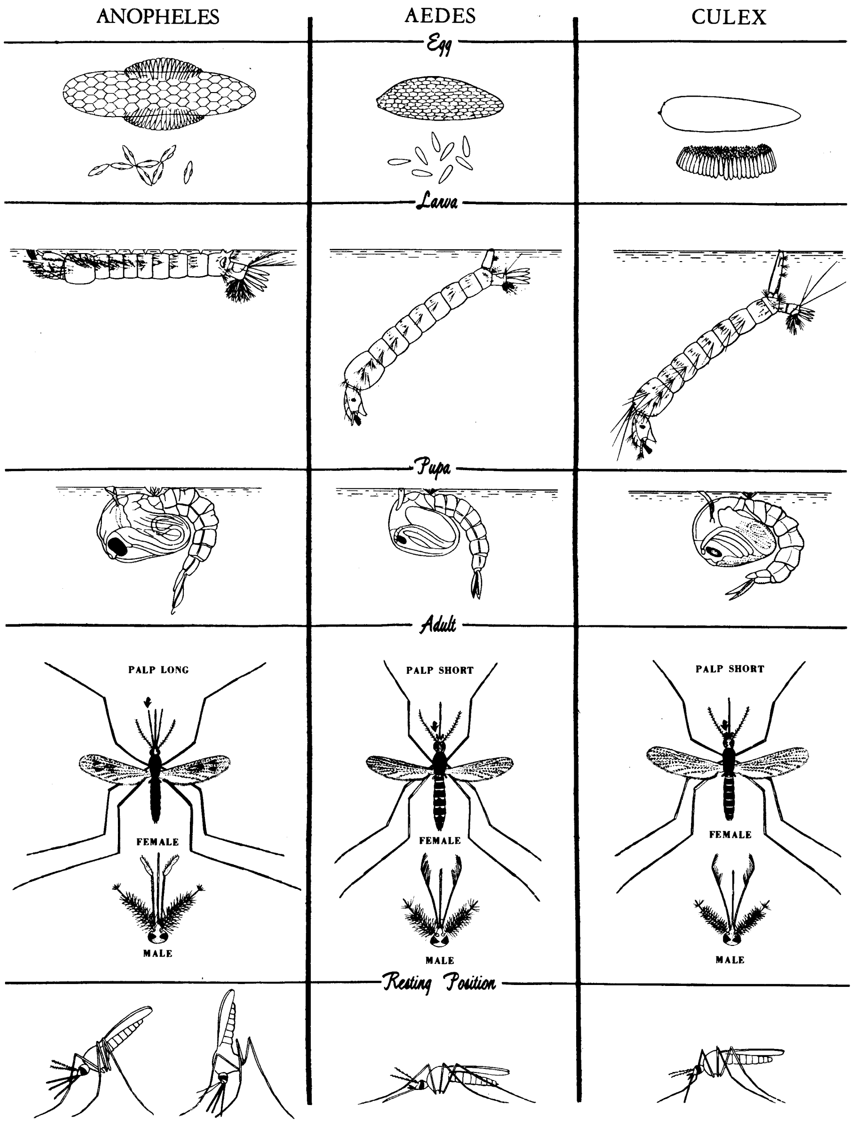

FIGURE 1.—Characteristics of three common mosquitoes.

probably will not travel far from their sources. On the other hand, mosquitoes may travel several miles when adequate food supplies are not available near their larval habitats. The flight range of the *Anopheles* and some *Culex* mosquitoes is usually considered to be about 1 mile, although some species frequently travel several miles; for example the encephalitis mosquito *Culex tarsalis* has flown as far as 10 miles. Most *Aedes* and *Psorophora* species are strong fliers and are known to range several miles from their larval habitats.

Mosquito Sources on Irrigated Farms

Studies in irrigated areas have shown that mosquitoes are often produced in both "on-field" and "off-field" aquatic habitats on irrigated farms. Natural mosquito-producing habitats occur in most irrigated areas, but manmade sources are usually far more important.

On-Field Sources

Prolific mosquito production often occurs in low areas on fields used for pastures, hay meadows, and other close-growing forage crops when irrigation water remains ponded long enough for the larvae to mature (fig. 2). Surface water must be present for at least 4 or 5 days for the aquatic stages to mature and produce adult mosquitoes. Rice is the only important field crop in America that thrives when flooded this long. Mosquitoes are sometimes produced on irrigated fields planted to row crops, such as cotton, but usually ponded water is not present on these fields long enough for the aquatic stages to complete their development.

Observations in several areas have shown that when irrigation water is ponded on pastures and hay meadows long enough to produce mosquitoes, the desirable forage grasses and legumes are frequently killed and replaced by wetland plants, which are less desirable from an agricultural standpoint. Thus, the extended flooding that is favorable for mosquito production is unfavorable for growth of common field crops.

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FIGURE 2.—Ponded areas at lower end of irrigated fields are important sources of mosquitoes. In addition, such ponding often damages crops and interferes with cultivation and harvesting.

In California, tremendous numbers of *Aedes nigromaculis* are produced in ponded areas on irrigated pastures. Some of these pastures are irrigated 10 to 15 times from April through October, and a brood of mosquitoes may be produced in the ponded areas that remain after each irrigation. Investigations in the Milk River Valley of northern Montana showed that over two-thirds of all mosquito production (mostly *Aedes dorsalis* and *A. vexans*) in a 5,000-acre study occurred in ponded areas on irrigated fields, pastures, and western wheatgrass meadows. In this valley the irrigation water frequently remains ponded on the hay meadows long enough to produce *Culex tarsalis*, the encephalitis mosquito. Studies in western Nebraska showed that large numbers of both *Culex tarsalis* and *Aedes* were produced in ponded areas on irrigated pastures and hay meadows along the North Platte River. The use of irrigated mountain meadows for producing hay and grazing of livestock is widespread in the Rocky Mountain States. In many valleys the bottom-land meadows are flooded almost continuously throughout the spring and early summer. Ponding also occurs in low areas after irrigation later in the season. Such extensive aquatic habitats are very favorable for producing mosquitoes in irrigated areas.

In addition to depressions on irrigated fields, water sometimes remains ponded in field laterals and drains long enough to produce the encephalitis and other irrigation mosquitoes (fig. 3). This condition occurs most often in areas having fine-textured soils and poor underdrainage. Field laterals and drains that contain excessive amounts of vegetation are more favorable for mosquito production.

Mosquitoes may also be produced in the residual water in various control structures, such as drops, particularly when they contain tum-

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FIGURE 3.—Water ponded in field laterals may produce mosquitoes.

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FIGURE 4.—Residual water in various control structures, such as drops, may produce mosquitoes.

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FIGURE 5.—Flooding ricefields often results in prolific mosquito production.

bleweeds and other debris (fig. 4). Mosquito production in such structures is usually of minor importance in comparison with that in other types of on-field aquatic habitats.

Ricefields constitute a special type of on-field mosquito source, since the type of flooding used for growing rice is favorable for mosquito production (fig. 5). In ricefields of the Mississippi Delta and gulf coast areas, large numbers of *Psorophora confinnis* and *Psorophora discolor* are produced by intermittent flooding, and *Anopheles quadrimaculatus*, the malaria mosquito, is produced by constant flooding. The ricefields in California are usually flooded throughout the growing season, and they provide favorable aquatic habitats for *Culex tarsalis* and *Anopheles freeborni*. In addition, large numbers of *Aedes nigromaculis* and *Aedes dorsalis* are frequently produced by the initial flooding of the ricefields.

Off-Field Sources

In many western irrigated areas, widespread and prolific mosquito production occurs in a variety of aquatic habitats located outside the boundaries of irrigated fields. These mosquito-producing areas include roadside ditches, borrow pits, depressions on nonarable land, and numerous other undrained areas that are flooded by waste irrigation water from fields and other sources (figs. 6-8). Such aquatic habitats often contain dense vegetation, which makes them highly suitable for mosquito production. Both semipermanent and permanent water areas are

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FIGURE 6.—Large numbers of mosquitoes are often produced in undrained borrow pits and roadside ditches, which collect waste water from irrigated fields.

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FIGURE 7.—Culverts placed too high result in ponding suitable for mosquito production.

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FIGURE 8.—Improperly maintained drainage ditches with sluggish flow and ponding are suitable for mosquito production.

favorable for the production of *Culex tarsalis*. Areas with fluctuating water levels also may produce large numbers of *Aedes* species.

These off-field habitats accounted for more than one-fourth of the total mosquito production on a 5,000-acre study area in the Milk River Valley of northern Montana. In the North Platte River Valley of western Nebraska, depressions on nonarable land, roadside ditches, borrow pits, and other undrained areas flooded by runoff from irrigated fields and overflow from conveyance systems were important sources of both *Culex tarsalis* and *Aedes* mosquitoes. Playas or land-locked depressions, flooded by runoff from irrigated fields, were responsible for three-fourths of all mosquito production on study areas in the Texas High Plains (fig. 9). These playas produced large numbers of *Culex tarsalis* and several other species of irrigation mosquitoes.

Reservoirs and ponds are used on some farms for storage and regulation of irrigation water. The conditions associated with farm impoundments that are conducive to mosquito production are basically similar to those connected with large reservoirs. They include (1) emergent or floating vegetation or both in shallow-water areas (fig. 10), (2) accumulations of flotage and debris in shallow-water areas and embayments protected from wave action, (3) undrained depressions within the fluctuation zone (fig. 11), and (4) seepage areas below dams.

Aedes mosquitoes may be produced in reservoirs where water levels fluctuate, alternately exposing and inundating shallow vegetated areas. Several species of permanent-water mosquitoes may be produced in reservoirs having shallow-water areas with emergent vegetation or flotage protected from wave action (fig. 10). In the West, *Culex tarsalis* mosquitoes

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FIGURE 9.—Major sources of mosquitoes are playas or land-locked depressions, which collect runoff from irrigated fields.

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FIGURE 10.—In irrigation reservoirs and ponds, conditions favorable for mosquito production are created by emergent or floating vegetation in shallow-water areas and embayments protected from wave action.

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FIGURE 11.—Mosquitoes also are produced in undrained depressions within fluctuation zone of reservoirs and ponds.

are often found in reservoirs and in the seepage areas that develop below the dams. In the East, *Anopheles* mosquitoes are produced in similar habitats.

Mosquito sources are sometimes associated with irrigation-distribution systems, which convey water to the farm ditches. Some of these canals may pass through nonirrigable lands. A large amount of irrigation water is often lost by seepage from unlined canals and laterals located in pervious material. In areas with poor underdrainage, seepage losses alone or in combination with deep percolation from irrigated fields often result in marshes and ponded water in roadside ditches, borrow pits, and other low areas (fig. 12). In many western irrigated areas, such aquatic habitats created by seepage produce large numbers of mosquitoes. Permanent and semipermanent seepage areas are especially favorable for the production of *Culex tarsalis*, the common encephalitis vector. *Aedes* mosquitoes are also produced in seepage areas that have fluctuating water levels.

Mosquito production sometimes occurs in various other off-field aquatic habitats associated with farm irrigation-conveyance systems. These include blocked natural drainageways (fig. 13), canals and laterals choked with vegetation (fig. 14), areas flooded by overflow from canals and laterals, and other surface pools created by leakage from or retained in conveyance channels and structures during nonoperational periods. Although these types of aquatic habitat contribute to the total mosquito problem, they are generally minor factors compared to those caused by seepage and the other off-field mosquito sources.

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FIGURE 12.—Borrow pits, roadside ditches, and numerous other depressions are often flooded by seepage from unlined irrigation canals and laterals. Such aquatic habitats are major sources of mosquitoes in many irrigated areas.

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FIGURE 13.—When irrigation canals block natural drainageways, resulting ponds are often suitable for mosquito production.

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FIGURE 14.—Mosquitoes may be produced in canals and laterals overgrown with vegetation. Mosquito sources are sometimes created by overflow from improperly maintained channels.

INTERRELATIONSHIPS OF MOSQUITO PREVENTION AND OTHER INTERESTS

Relationships to Irrigation Agriculture

Various structures and systems have been developed in connection with good farm irrigation practices. Most of the on-field and off-field mosquito sources previously described are associated with poor irrigation and drainage practices, including inadequate land preparation; use of farm layouts and irrigation methods that do not fit the land, crops, or water supply; application of water in excess of crop requirements; improper preparation and maintenance of reservoirs and conveyance systems; and inadequate drainage systems for removal of excess water. Such practices also cause excessive water losses, waterlogging of fields, salt and alkali accumulations in soils, damage to soil structure, leaching of plant nutrients, and reduced crop yields. These problems are intimately associated with losses of water that occur when an irrigation project is developed and water is used for crop production. Such water losses often contribute to conflicts of interest between various agencies concerned with the use of water.

Competition and growing demands are demonstrating the importance for all consumers to manage and to use water more efficiently. Irrigation waste water is a major factor in the development of habitats suitable for mosquito production. Research, experience, and technological advances have provided many practical techniques for reducing irrigation water losses. In the following sections are described some of the basic problems in soil and water management on irrigated lands and how they are being solved.

Water Losses During Storage, Conveyance, and Application

It is not uncommon to find irrigation projects where only 25 percent of the water actually diverted for irrigation purposes is used by the crops grown. The remaining 75 percent is lost during storage, conveyance, or application. Ultimately a large part of this "lost water" returns to streams or ground-water reservoirs and is available for other users. Much of it collects in surface ponds and seep areas unless carried away by natural or constructed drainage systems.

Reservoirs.—Water collected or diverted into storage reservoirs is subjected to losses by evaporation, seepage, and consumption by noneconomic vegetation in and surrounding impoundments. Mosquito production is often directly associated with the last two losses. Considerable research is underway to develop methods for controlling such water losses.

Reservoirs often contribute to seepage problems if the underlying material is porous or fissured. It is often possible to treat small reservoirs with bentonite or other sealing materials to reduce seepage losses. If the reservoir involved is only a few acres in size, plastic liners can be used to decrease seepage loss and to control vegetative growth around the edges of a reservoir and thus advantageously reduce mosquito production. The initial high cost of materials, their relatively short life, and the damage resulting from rodents and birds are factors still to be resolved before wide usage of such materials can be expected.

Many reservoirs have shallow embayments and marginal areas that are flooded only when the water level is high. A system of dikes can sometimes be used to confine the water to the main reservoir basin and thereby reduce growth of vegetation in shallow-water areas and decrease use of water in evapotranspiration. Such a practice would also eliminate potential mosquito sources.

Canals, Laterals, and Ditches.—Evaporation of water in transit and consumption by vegetation on properly maintained ditchbanks are negligible. In contrast, seepage losses from unlined irrigation canals have been estimated at 25 to 50 percent of all the water diverted into the canals. Seepage losses in 1949 totaled 3,900,000 acre-feet of water on U.S. Bureau of Reclamation projects alone. Seepage losses also result in waterlogging of adjacent lands, which generally makes farming operations and crop production impossible without the added cost of expensive drains. At the same time, larger canals must be built to carry the additional water that will ultimately be lost to seepage before reaching the land to be irrigated. The alternative, of course, is to line or to place in closed conduits those reaches of canal that demonstrate excessive permeability.

Considerable effort is being directed toward the development of economical canal linings to reduce excessive seepage losses. Nonreinforced concrete canal linings and buried asphaltic membranes are the most widely used materials at the present time, but costs are high. Other materials used include asphaltic concrete, prefabricated asphaltic membranes, asphaltic emulsions, compacted earth, bentonite, and soil cement. Considerable attention is currently being given to low-cost liners utilizing plastic films and to laminated asphalt-jute liners for laterals and on-farm ditches. Most of these developments are still in the experimental stage. Nonetheless, they offer promise of eventually controlling the major seepage losses and mosquito production associated with them.

Operation of conveyance systems can also result in substantial losses of water where demand is affected by such factors as weather and holidays. Water must be wasted to protect the canal when the demand is erratic. Unless adequate wasteways and drains are provided, such water may periodically overflow wasteland and result in ponding ideally suited to mosquito production.

Water Application.—Irrigation-application efficiency (percent of water applied that remains in the crop-root zone) is affected by the farm-system layout, degree of land preparation, and the skill of the irrigator. The Bureau of Reclamation has reported farm efficiencies of 34 to 70 percent on Federal irrigation projects. In other words, 30 to 66 percent of the water applied on farms is lost to deep percolation, evaporation, and surface runoff. Some of this water is reused as return flow on downstream projects, but some of the losses cannot be recovered. This water must be carried away in surface or subsurface drains to avoid crop damage due to ponding or high water table or both and to reduce mosquito sources.

Irrigation and cropping methods should fit the soil, slope, crop, and water supply. Erosion, alkali damage, waterlogging, and undue water loss should be avoided. An adequate inventory of soil and water resources and selection of irrigation methods to fit these conditions are required. Distribution systems must be developed to get enough water to all parts of the farm when needed, and the land must be prepared so that the water can be applied with high efficiency. When completed, the irrigation system must be operated properly to attain maximum application efficiency. This operation requires adjustment of stream size to intake rate, length of run, furrow size or width of border, and stage of crop development. Also, one must have a knowledge of the water-holding capacity of the soil and crop-rooting depth in order to apply the correct amount of water.

For a detailed discussion on design and operation of irrigation systems, refer to "Irrigation on Western Farms," prepared by the Bureau of Reclamation and the U.S. Soil Conservation Service (see Selected References at the end of this bulletin). It is important to realize that low application efficiency may occur with the best designed irrigation systems if the operator manages his water poorly. Conversely, the best irrigator cannot achieve maximum efficiency if the irrigation system he operates is not adequately designed and constructed.

Soil and Water Management

Intake Rate.—An efficient irrigator requires a knowledge of intake rates to determine how long water should remain on the land to replenish the crop-root zone reservoir. Management of soils to maintain adequate intake rates is considered by some authorities to be the primary problem associated with crop production on irrigated lands in arid and semiarid regions.

Many irrigation projects have been developed that at best were marginal from the standpoint of inherent soil capability. In some areas, topography has been ideally suited to land development and distribution of irrigation water, but the soils have been predominantly fine-textured clay with poor internal drainage. In such instances, intake rates, once the topsoil has become wet, are practically nil. If the clay mineral is montmorillonitic, cracks develop upon drying. Irrigation then becomes a matter of applying the amount of water required to fill the cracks, which subsequently close by swelling.

Surface soil structures may be improved by alternate wetting and drying, and freezing and thawing, but seldom are they adequate to circumvent the problems associated with water application and distribution. When farmers do not know how much water is required to replenish the crop-root zone reservoir, they tend to irrigate for excessive periods. This results in considerable waste water collecting at the lower end of fields. Without adequate surface drainage, water accumulates in low areas and creates excellent mosquito sources.

Research conducted on clay soils in the Milk River Valley of Montana illustrates how mosquito production can be controlled by applying good soil- and water-management practices. The traditional practice of wild flooding western wheatgrass for 30 to 40 days in the spring produced ideal habitats for mosquito production. Moreover, the crop yield averaged only about 0.5 ton of poor-quality hay per acre. In contrast, installing a well-designed border irrigation system, utilizing irrigation water as needed, and adopting good fertility practices resulted in a tenfold increase in yield of high-quality hay and no mosquito production. Ponding of water was eliminated by applying only that amount required to refill the crop-root zone. Although this research demonstrated conclusively how the farmer could manage his water and soil to increase crop yields and reduce mosquito production, adoption of such practices on a project basis is often difficult in view of the economics of low water cost and increased labor requirements.

In many instances, low intake rates of soils cannot be greatly changed. Minimum tillage when the soil is at optimum moisture conditions, subsoiling to break up impervious layers near the surface, vertical mulching, and other practices can sometimes improve water intake and reduce runoff. The choice of practice depends on the nature of the problem. At the Owyhee project in Oregon, deep plowing (30 inches) of laminated, slowly permeable silt layers within the soil profile increased intake rates and crop yields manifold. In the Texas High Plains, a Pullman silty clay loam responded to a deep-rooted crop of alfalfa. Here, a fivefold increase in intake rate persisted over a 3-year period, illustrating the benefits that can accrue from crop rotation. Minimum tillage practices in the Salt River Valley of Arizona have been highly successful in facilitating water intake to depths of 6 feet. These examples illustrate adoption of practices by farmers to "live" with situations involving low intake rates and still make efficient use of available water supplies.

Intake rates can also be affected by the amounts and kinds of salt that accumulate in the soil profile. These salts may be present in the soil before it is ever irrigated or they may accumulate from application of irrigation water containing large amounts of dissolved salt. For example, in some areas the 2 to 4 acre-feet of water normally applied in a given year, much of which is evaporated or transpired, can add 20 tons of salt to the soil profile. Salts must be leached periodically by applying additional water in order to maintain a favorable salt balance. If natural drainage is inadequate, artificial drainage must be provided to dispose of the excess water and salt.

Where alkali problems develop, soil and water management is more difficult. Alkali soils have poor structure with low intake rates. Water that ponds in alkali areas remains until lost by evaporation. Improvement of alkali soils requires lowering the water table and replacing sodium in the soil with soluble calcium or other divalent cation (gypsum is commonly used), removing salts by leaching, and rearranging and aggregating soil particles to improve soil structure and intake rate. Reclamation of alkali soils is usually slow, requiring application of water for leaching. In general, about 1 acre-foot of water is required for leaching purposes for every ton of gypsum applied. It is not uncommon to find a gypsum requirement of 10 tons or more per acre for some soils.

Timing Irrigations.—The magnitude of water loss through deep percolation and runoff at the lower end of fields is intimately associated with the farmer's uncertainty as to "when to irrigate a crop" and "how much water should be applied." Many farmers irrigate from experience. Others may be restricted to a given irrigation regime determined by a prearranged water-delivery schedule on a project rotation basis. The farmer who can get water on demand has maximum flexibility and opportunity to use water most efficiently.

More crops are overirrigated than underirrigated, especially in areas where water is plentiful and cheap. In such areas the farmer will often substitute water for the additional labor required to do a good job of irrigating. When water is limited and its cost is high, good irrigation principles are more often utilized. Not only does overirrigation waste water but soluble plant nutrients may be leached to depths below the rooting zone. Some crops, like alfalfa, are susceptible to damage by prolonged flooding during hot periods and either die or yield poorly. Ponding from overirrigation likewise produces mosquitoes.

Frequency of irrigation depends on soil-moisture storage capacity in the crop-root zone and the evapotranspiration rate. It is important for many agricultural crops to maintain continuous growth for optimum yields. Most recommendations favor irrigating when about 50 percent of the available moisture in the root zone has been used. During the peak growing period, when evapotranspiration rates are highest, a sandy soil might require an irrigation every 4 to 6 days, whereas a silty clay loam would not require irrigation for 14 days or more. Hence, the farmer needs a knowledge of the soil's water-holding capacity in order to properly schedule irrigations.

The problem is further complicated, since evapotranspiration rates for annual crops are not constant throughout the season, but generally increase from a low value at seeding to a maximum value at peak growth, followed by a gradual decrease as the crop matures. Moreover, periodic harvest of perennial crops, like alfalfa, also affects water use; rates are lower immediately after crop removal. In some areas climatic conditions markedly affect the rate of water loss, which is lower during wet, cool periods and higher during hot, dry periods.

Many soil and crop factors must be considered to properly schedule irrigations. Research has provided the farmer with techniques and information that can be used to do a better job of irrigating. Instruments to measure soil moisture are available commercially. If properly used, they show when a crop should be irrigated. Seasonal and periodic consumptive use of water (evapotranspiration) rates have been measured for many crops and are being utilized in a "bookkeeping" approach to scheduling irrigations. In the Columbia River Basin, evapotranspiration rates are estimated from evaporation pans and are furnished daily to the farmers by radio.

Experiments dealing with irrigation needs based on plant appearance and critical stages of plant development have practical application. For example, field beans growing on moist soils can be irrigated 5 days after the foliage changes from light green to dark green without affecting yield. Limited wilting of corn prior to tasseling has little effect on yield, but 4 to 6 days of wilt during the tasseling and silking period can reduce yield as much as 40 percent. If available information and techniques were applied to the timing of irrigations on farmers' fields, much of the water now wasted could be used to irrigate additional land.

Determining Amount of Water Applied.—In many areas the farmer irrigates on a 12- to 24-hour set or longer, depending on soil conditions and replenishment water required. He seldom actually measures water "on" and "off" his fields to determine how much he has applied. Several water-measuring devices are available, but most of them are not simple or rugged enough to be readily acceptable. The development of a vane meter by Parshall, though not extremely accurate, comes close to determining field requirements, but still requires standard channel sections at several points on the farm. It has the advantage, however, of portability and direct indication of flow measurement. Meters reading directly in acre-feet are now used in some areas, particularly where irrigation water is pumped. Research on water measurement continues to have a high priority in some hydraulic laboratories. Until the farmer is supplied a simple tool for measuring water accurately, runoff from irrigated fields will continue to be a problem.

Other developments may affect water-use efficiency. Low-gradient or level-basin irrigation systems show promise of being highly efficient. On Tripp fine sandy loam at Scottsbluff, Nebr., irrigation-application efficiency on bench-leveled irrigation basins has reached 90 percent with excellent distribution of water. With this system, the irrigator need only know the size of the irrigation stream and the time required to apply a given amount of water. In the Lower Rio Grande Valley, about 250,000 acres of irrigated land is now in level or low-gradient basins. Basin irrigation not only provides better control of the amount and distribution of irrigation water but permits collection and retention of rainfall often during high-intensity storms. The additional water from rainfall facilitates leaching of salts and supplements the limited irrigation water supply. Some problems are still to be resolved before low-gradient or level-basin systems will be widely accepted. Foremost among these are management of escarpments between benches, difficulties in maintaining the border level, susceptibility of some crops to flooding, and large streams required, but as water for irrigation becomes more scarce and more expensive, doubtless more low-gradient irrigation systems will be installed.

Water-Use Efficiency in Relation to Crop Needs.—Any practice that increases crop yields also increases water-use efficiency, expressed as the units of marketable crop produced per inch of water. Hence, it is important that all factors affecting production, such as soil-moisture availability, plant density, and fertility, be maintained in proper balance for most efficient use of water. If any one factor becomes limiting, maximum production efficiency cannot be expected.

Research has shown that increasing crop growth and yield with fertilizer results in some increase in the water required per acre to produce the fertilized crop. However, doubling yields does not double the water consumed. In fact, the increased evapotranspiration from fertilized crops seldom exceeds a 5-percent increase in water use, even though yields may be increased 200 to 300 percent. Maximum water-use efficiency comes with good soil and water management. Under such conditions, mosquito production is seldom a problem. On the contrary, low water-use efficiency often means too much water and high mosquito production.

Drainage.—Successful irrigation agriculture requires adequate natural or artificial drainage. Historically, first attention has been given to getting water to the land and drainage has been essentially ignored until problems have developed. Unfortunately many highly productive soils have become waterlogged and "salted out" through delays in providing adequate drainage. Of course it is not always possible to know in advance where drains will be required. However, when the need for and location of drains can be predicted, it is easier and less costly to provide drainage initially than to correct severe waterlogging and alkali conditions when they develop.

The principal source of water contributing to drainage problems arises from overirrigation and seepage from unlined canals. Such water losses can be reduced, as previously described. The operation of most irrigation systems results in some deep percolation and runoff losses that are difficult to avoid. In such cases, drainage facilities may be needed to prevent direct injury to crops, to minimize salt accumulation by leaching, and to allow proper timing of farming operations.

Both surface and subsurface drains are required on most irrigated land. Surface drains are necessary to remove excess irrigation water and runoff from precipitation. Subsurface drains are necessary for the removal of ground water that would result in a high water table. Surface drains to remove excess irrigation water usually are included as a part of the modern irrigation system; however, drains for the disposal of waste water were not included in many older systems. Runoff from precipitation is usually relatively small in irrigated areas in arid and semiarid regions because of low rainfall and because fields are small tracts isolated topographically by irrigation laterals and canals. Ditches for disposal of excess irrigation water are therefore often adequate for disposing of surface runoff from precipitation.

Subsurface drainage is usually the primary objective in western irrigated areas. Often the subsurface system provides for the removal of both surface and subsurface water. Drains may be either covered or open. Open drains often serve to remove both surface and ground water. Covered ones are seldom used as dual-purpose drains because of the increased cost of larger tile needed to accommodate surface runoff in addition to ground water. Subsurface drains are either relief or interception drains depending on their alinement with respect to ground-water flow. Relief drains are alined parallel to the direction of ground-water flow, and interception drains are installed about perpendicular to ground-water flow and are used also under some conditions where there is little or no slope of the water table.

The location of surface drains in irrigated areas is usually governed by the pattern of irrigation. Field drains are located at the lower end of rows or border strips and preferably adjacent to irrigation canals, fence rows, or roads. Control structures are generally provided so that drain water can be discharged into lower irrigation canals or conveyed over or under the canals to an outlet. If the discharge from drains is small in comparison to canal capacity, it may be possible to outlet into irrigation canals without danger of exceeding their capacity. Where the drain discharge is large in comparison to canal capacity, some type of canal crossing must be provided. Structures generally used for this purpose include culverts, inverted syphons or flumes, and bridges.

The pattern of subsurface drains in irrigated areas is similar to that used to solve drainage problems in nonirrigated areas. Drains are usually laid out on a parallel, gridiron, herringbone, or random pattern. Interception-type drains are most frequently used and are randomly laid out on a slight grade to maintain uniform depth. Main drain and outlet conditions for subsurface drains must meet the same requirement as surface drains in irrigated areas. Subsurface drains usually have greater depth; therefore, there is less opportunity to discharge into irrigation canals for reuse of water. Culvert-type crossings are generally used at irrigation canals. A high salt content of drainage water may prohibit its discharge into irrigation-water supply.

Most of the drains constructed in western irrigated areas have been the open type designed as dual-purpose subsurface drains. They have many advantages, but because of their depth and relatively flat side slopes, they may require rights-of-way from 60 to 100 feet wide. Such a right-of-way may require as much as 10 acres per mile of drain. Surface water is admitted to subsurface drains through grade-control structures of various types. The present trend is toward the construction of covered drains, since no land is removed from production, and if properly installed, they require very little maintenance. Many existing open drains are being rehabilitated as covered drains.

Open drains are often poorly maintained and become clogged with weeds and vegetation. The slow-moving ponded water creates an ideal habitat for mosquito production. Replacement of open drains with covered drains is therefore often mutually beneficial to irrigation agriculture and mosquito control.

The "pump-back" systems, which are currently being used on sloping lands in California, not only allow for more efficient use of water but at the same time eliminate mosquito habitats. In these systems, runoff from irrigated fields is collected in basins and is pumped back to the head ditch for redistribution. The water is recirculated, so to speak, until the amount required has entered the soil. In the Texas High Plains, runoff water from rainfall and irrigation often collects in playa lakes. Not only would the use of pump-back systems solve the mosquito problem associated with ponded water, but in an area where ground-water irrigation supplies are rapidly becoming depleted, such a practice might well conserve and extend available water supplies.

Pump-back systems should maximize application efficiency on graded irrigation systems, particularly where restricted intake rate is a problem. This development also illustrates how a conservation practice works to the advantage of several interested groups—those interested in eliminating mosquito habitats and those interested in conserving limited water supplies while at the same time improving irrigation practices and reducing a water source that contributes to drainage problems.

Relationships to Aquatic Wildlife Conservation

Some years ago mosquito control and aquatic wildlife conservation interests were generally incompatible. During recent years a cooperative approach to the development and management of aquatic wildlife resources often results in practices mutually beneficial to both mosquito prevention and wildlife interests.

Aquatic wildlife—fish, waterfowl, certain fur animals, and scores of shore, wading, and diving birds—must have a favorable aquatic environment in order to thrive. The following sections point up some of the basic requirements of aquatic wildlife and suggest how these requirements may be integrated with those for mosquito prevention on irrigated farms.

On-Field Relationships

As previously mentioned, retention of ponded water on irrigated lands long enough to produce mosquitoes is injurious to all field crops except rice. If good irrigation and drainage practices are followed, on-field relationships between mosquito prevention and aquatic wildlife will be of concern only in rice-farming areas. Since rice culture does not usually involve permanent year-round flooding, these relationships involve waterfowl and shore birds, but not fish. Top minnows are sometimes stocked in ricefields to aid in mosquito control, but as such they do not constitute a fishery resource.

Ricefields flooded after harvest may provide excellent resting and feeding grounds for waterfowl. If the flooding takes place at the end of the mosquito-production season, it will not create a mosquito problem. However, if the flooding occurs during the mosquito season, it may result in prolific and extensive mosquito production.

Off-Field Relationships

The major relationships between mosquito prevention and fish and waterfowl production on irrigated farms involve off-field habitats. These habitats include (1) systems for the collection and disposal or utilization of excess irrigation water, (2) small storage or regulating reservoirs, and (3) irrigation-conveyance systems. All of them have considerable potential as productive habitats for fish and waterfowl, and can usually be managed in a manner compatible with mosquito prevention.

Irrigation runoff water is often wasted, and this waste water creates some of the most important mosquito sources on irrigated farms. In some areas, nonarable land is wild flooded with excess irrigation water for use by ducks and other waterfowl. Such areas are often highly favorable for the production of *Aedes* mosquitoes. Abatement districts in California and Utah spend large sums of money to control mosquitoes produced on waterfowl areas of this type.

The rapidly growing shortage of our natural water resources demands that excess irrigation water be utilized to the fullest extent possible rather than wasted. One of the most valuable types of utilization is to create impoundments for the production of fish and waterfowl (figs. 15 and 16). Correct design and construction, and proper management

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FIGURE 15.—Farm impoundments are valuable source of fish and waterfowl production. If properly designed, they may produce fewer mosquitoes than previous unmodified habitats.

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FIGURE 16.—Farm fishpond such as this with clean, abrupt shoreline and open water exposed to wave action will produce very few mosquitoes. Adequate water-control structures are necessary to prevent flooding of marginal vegetation for extended periods during mosquito breeding season.

and control of water levels and aquatic vegetation in these impoundments, are essential for both mosquito prevention and efficient production of fish and waterfowl. In general, a properly constructed and managed wildlife impoundment will produce only a fraction of the mosquitoes that would be produced in the same area if it were unmodified and subjected to haphazard flooding with excess or salty irrigation water.

An important construction feature for small farm fishponds is to eliminate shallow-water areas insofar as possible. Water less than 2 feet deep encourages the growth of both submerged and emergent aquatic plants. These plants are undesirable in a fishpond because (1) they shelter small fish so that too many survive and exceed their food supply, resulting in a stunted population; (2) they may absorb valuable nutrients from the water and the bottom, tying them up on compounds the fish cannot use; and (3) they interfere with fishing, boating, and swimming. These same plants also add to the problem of mosquito control.

In impoundments used primarily for waterfowl, both submerged and marginal emergent aquatic plants are desirable. The submerged aquatics may grow in water with depths up to 6 or more feet, depending on water transparency. Such areas should comprise about 80 percent of the total water surface for an ideal waterfowl habitat. These plants not only serve as food for waterfowl but also harbor small aquatic animals, such as insects, crustaceans, and mollusks, which are highly valuable, if not essential, in the diet of young ducks because of their high protein, phosphorus, and calcium content. Some of the most valuable submerged waterfowl food plants, such as sago pondweed (*Potamogeton pectinatus*), may be produced in such open-water areas without creating a significant mosquito source if the open areas are 2 feet or more deep and at least 30 feet wide.

Marginal, terrestrial, and emergent aquatic plants are necessary to provide nesting cover for waterfowl, and some of them are also utilized as food. Some of the tall emergent species, such as hardstem bulrush and cattail, provide excellent nesting cover for geese and ducks and do not serve as important sources for mosquito production (fig. 17). The shorter, more flexuous species, such as saltgrass (*Distichlis stricta*), are less satisfactory as nesting cover and are among the most prolific sources of mosquito production, particularly when growing in shallow water. However, they may provide feeding areas for water birds. Steepening of pond margins is of considerable value in limiting mosquito production. Although steepening of pond margins may reduce the total amount of wildlife habitat, it can increase the availability to waterfowl of "ditchbank" types of marginal vegetation. This vegetation is often used as nesting cover, and some species, such as rice cut-grass, millet, and smartweed, are also excellent waterfowl food plants. In larger ponds, small islands may be constructed to provide this type of cover.

The installation of adequate water-control structures is required in the construction of small wildlife impoundments for collecting irrigation runoff. This is necessary for both wildlife management and mosquito prevention. These structures should hold the water at constant levels

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FIGURE 17.—Tall, dense, emergent vegetation, such as bulrushes in background, provides food and nesting cover for ducks and geese and good habitats for muskrats, with minimum of mosquito production. Open grassy vegetation to left of muskrat house is likely to produce mosquitoes.

or raise or lower it to any desired level. Where feasible, they should also provide for bypassing excessive flows to prevent undesirable flood surcharges.

The main phases of water-level control in permanent ponds are constant pool, surcharge, recession, and cyclical fluctuation. The effect of each of these phases on mosquito prevention and fish and wildlife management may be beneficial or detrimental, depending on timing and magnitude.

Constant pool levels in fishponds are particularly important during the spring spawning period of game fish to prevent stranding of the eggs before they hatch. A constant pool level during this same period usually benefits mosquito prevention by limiting invasion of undesirable marginal vegetation. Surcharge flooding of pond margins during the waterfowl breeding season may inundate nesting areas and cause catastrophic losses of eggs and young birds. A brief flood surcharge may benefit mosquito prevention by stranding marginal debris and flotage, but it should be carried out in the early spring before the beginning of the waterfowl nesting season.

Employed without discretion, seasonal recession and cyclical fluctuation may be deleterious to wildlife and fish, but if properly applied, these measures may be one of the most effective tools in wildlife management. For example, a fall drawdown restricts the amount of water and food available to migrating waterfowl. On the other hand, a fall drawdown or cycle of fluctuation is often beneficial in permitting predatory game fish to better utilize small rough fish, which would interfere with reproduction by the desirable game species. Seasonal recession and cyclical fluctuation are also important in mosquito prevention, but here again they must be used properly. For example, early and excessive seasonal drawdown is very favorable to mosquito production, in that it increases the invasion of undesirable marginal plants, which will be sources of mosquito production during the following year.

It is important for both mosquito prevention and fish management that any marginal depressions be connected with the main pond by ditches so that they will be self-draining. The normal seasonal pattern of water-level fluctuation in natural ponds is high water in late winter and early spring, a relatively constant level in late spring, and a gradual recession during summer and early fall. The most effective water-level schedules for both wildlife management and mosquito prevention are usually adaptations of this natural cycle.

In situations where there is no year-round source of water, it is impossible to develop permanent fishponds, and waterfowl impoundments must be managed on the basis of seasonal or intermittent flooding. Where the water supply is variable from year to year, it is sometimes possible to construct a series of small ponds and fill only those for which water is available. In some situations, pond basins dewatered during the summer may be planted with cultivated crops or seeded and allowed to produce natural waterfowl food plants, such as wild millet (*Echinochloa crusgalli*), and then reflooded in late fall after mosquito breeding has ended to provide resting and feeding grounds for migrating waterfowl (fig. 18).

Small farm impoundments are often damaged by muskrats, which burrow through the dams and cause them to leak. Ideal habitats for muskrats are shallow marsh areas with only about 20-percent open water. Therefore, fish and waterfowl ponds with steep banks and limited

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FIGURE 18.—Wetland types of vegetation, such as this wild millet, may provide valuable nesting and feeding areas for waterfowl if located adjacent to farm impoundments.

marginal vegetation will discourage muskrats. Deliberate use of irrigation runoff to create muskrat habitats usually creates many more mosquito problems than the use of this water for fish or waterfowl impoundments.

Irrigation canals and drainage ditches frequently provide valuable habitats for fish and waterfowl, particularly in the Western States. If properly maintained, these waterways do not create important mosquito problems and their use in fish and waterfowl management is compatible with mosquito prevention. Irrigation canals make excellent habitats for trout, especially brown trout, if the flow is maintained year round. A year-round or only a growing-season flow prevents the establishment of terrestrial and emergent aquatic plants in the canal bed. A bypass structure provides for return of water to the main stream during the off-irrigation season. When it is necessary to drain canals for repair or cleaning operations, it is often possible to salvage most of the fish stranded in the canal by seining or shocking and transplanting them to other habitats.

Constant-flow canals and drainage ditches are often used by waterfowl that feed on submerged vegetation and aquatic insects. They make excellent areas for "jump hunting." Such use does not interfere with mosquito prevention, which is primarily concerned with the control of marginal and emergent vegetation rather than submerged aquatics.

Seeped areas from irrigation canals are a common source of mosquito production. They may be used by waterfowl, but they do not provide full potential for waterfowl unless properly developed. Where control of canal seepage is not practicable, it may be desirable to develop fish or waterfowl impoundments to utilize the seepage water. This will not increase the mosquito problem if the same principles are followed as previously outlined for collection and disposal of irrigation runoff.

BASIC PRINCIPLES AND PRACTICES FOR MOSQUITO PREVENTION

As indicated previously, the ultimate solution to mosquito problems associated with irrigation should be based on source-reduction measures aimed at preventing, eliminating, reducing, or suitably modifying manmade aquatic habitats on both irrigated and nonirrigated lands. On irrigated farms, this can be accomplished largely through the use of good irrigation and drainage practices that will insure high crop yields without excessive water losses or decreased soil productivity. The full utilization of source-reduction measures will greatly minimize the need for repeatedly applying chemicals for mosquito control.

Both on-field and off-field mosquito sources commonly found on irrigated farms can be prevented, reduced, or eliminated through applying the principles and practices outlined in the following sections. The agricultural benefits to be derived from these practices will usually greatly exceed the cost of applying them. Some of the practices will also be mutually beneficial to aquatic wildlife conservation. Thus, in many situations, the prevention and control of mosquitoes and mosquitoborne diseases may be accomplished cost-free if these basic principles and practices are followed.

Impoundments

(1) Prior to impoundage, the reservoir basin should be prepared as follows:

(a) The normal summer fluctuation zone of the permanent pool should be completely cleared, except for isolated trees and sparse vegetation along abrupt shorelines or in large open areas that will be exposed to wave action.

(b) Timber rooted below the normal summer minimum pool level but extending above that elevation should be cleared. In some situations, such timber may be felled and securely tied down in lieu of disposal. This practice sometimes has advantages for fisheries management.

(c) All depressions, marshes, and sloughs that will be flooded by the reservoir at maximum pool level and that will retain water at lower pool levels should be connected with the main reservoir by drains to insure complete drainage or fluctuation of water within them.

(d) If the summer fluctuation zone of the permanent pool is limited to a few feet, consideration should be given to "building out" mosquito-producing areas by deepening or filling the more extensive shallow-water areas. This would minimize the need for repetitive measures for controlling vegetation and mosquito production.

(e) Provision should be made for utilizing water-level management to minimize conditions favorable for mosquito production to the maximum degree permitted by the primary functions of the reservoir.

(2) After impoundage, dense vegetation should be removed periodically from flat, protected areas within the normal summer fluctuation zone of the permanent pool in all potential mosquito-producing areas located within mosquito flight range of human populations or recreational areas frequented by large numbers of persons. Vegetation, debris, and flotage should be removed periodically from all drains to insure free flow.

Irrigation-Conveyance and Distribution Systems

(1) Lining, closed pipe, or other satisfactory seepage control measures should be provided for all sections of canals and laterals located in porous material where excessive leakage would result in waterlogged areas, seeps, and ponds.

(2) Drains should be installed to prevent ponding of excess irrigation water and natural runoff along the upper side of canals and laterals. All drainage crossing or inlet structures should be placed on grade to avoid ponding.

(3) All borrow areas should be self-draining to keep them from retaining ponded water.

(4) Where possible, provision should be made to prevent the bottom of canals and laterals as well as turnouts and other control structures from retaining residual water when they are not being used.

(5) Effective measures should be provided to prevent ponding of leakage from water-control structures.

(6) Every effort should be made to establish delivery schedules that will provide adequate but not excessive amounts of water at proper intervals to insure efficient irrigation of the crops concerned.

(7) Vegetation and debris that retard normal flow should be periodically removed from all conveyance channels, water-control structures, and drains.

Irrigated Lands

(1) The farm-supply system, drainage system, and field layouts should be properly fitted to the topography, soil, water supply, crops to be grown, and irrigation methods to be used.

(2) All surface-irrigated fields should be properly leveled or graded to provide for efficient water application and removal of excess water without ponding.

(3) Adequate drainage systems should be provided for removal of excess water from all irrigated fields.

(4) Irrigation methods should be used that will provide optimum irrigation efficiency.

(5) Application of irrigation water should be limited to that required to fill the crop-root zone plus unavoidable losses and excess leaching water to prevent damaging accumulation of salts in the root zone.

(6) Cultural and soil-management practices that will develop and maintain good soil structure and infiltration rates should be utilized to the fullest extent possible.

Drainage Systems

(1) Trunk drainage systems should be installed to insure complete removal and proper disposal of excess irrigation water, natural runoff, and seepage from both irrigable and nonirrigable lands affected by the distribution and use of irrigation water on the farm.

(2) Drainage ditches should be designed, constructed, and maintained so as to minimize ponding in the channels and to insure free flow at all times.

(3) Provision should be made to prevent water from ponding behind spoil banks.

(4) Underdrains, culverts, inlets, and similar structures should be placed on grade to prevent ponding.

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